On the Impact of Cut-Through Links in Epidemic Broadcasting

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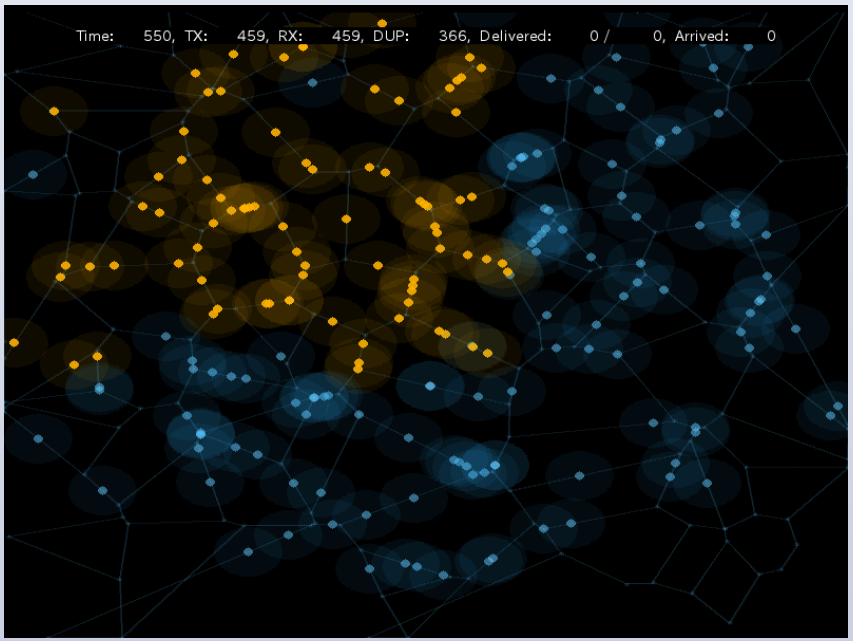
Outline

Background

- DTN (Delay/Disruption-Tolerant Networking)
  - Realize end-to-end communication even when communication links in the network are not always functioning properly
  - Regarded as a promising technology for realizing communication infrastructure under disasters and/or extreme situations
- Research question
  - How cut-through links (i.e., small number of wired (stable) communication links) are effective in DTNs?

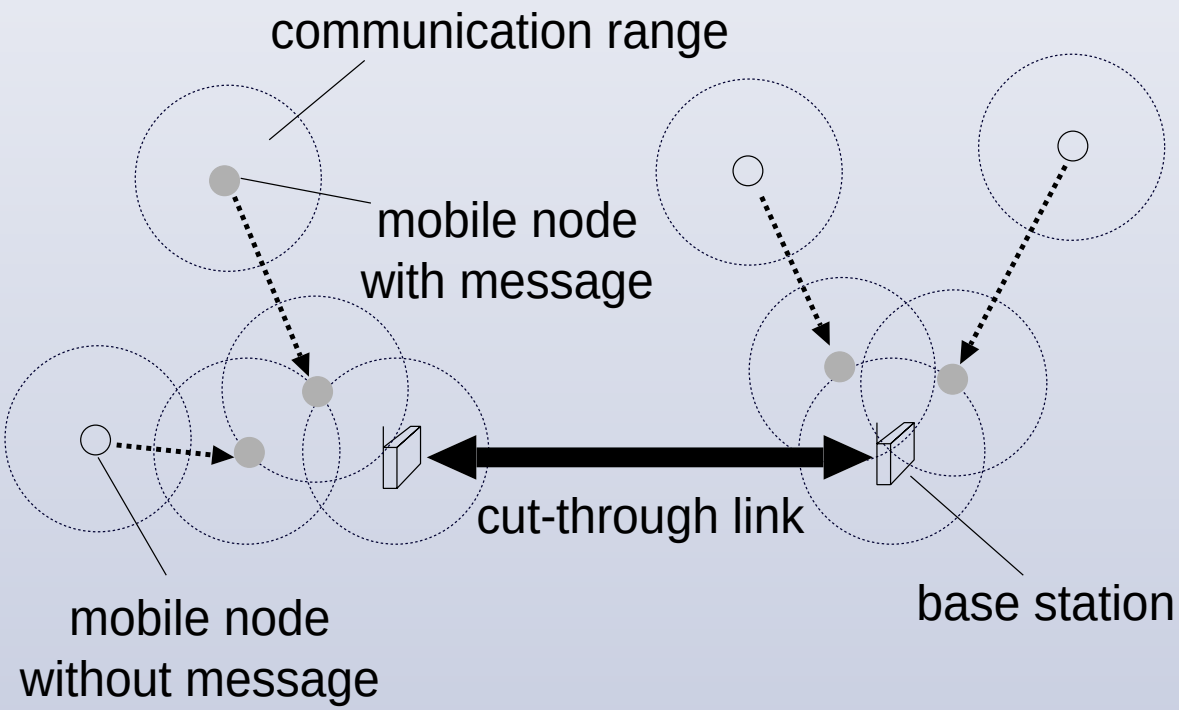
Epidemic Broadcasting

- Store-carry-and-forward communication for disseminating a message from a single source node to all other nodes
- P-BCAST (PUSH-based BroadCast)
  - The simplest epidemic broadcasting algorithm
  - Every node carrying a message always propagates to any encoutering nodes



Cut-Through Link

- A wired (i.e., stable) communication link connecting multiple points on the field
- Base stations are connected with cut-through links
- Messages can be forwarded among (distantly located) base stations



Research Objective

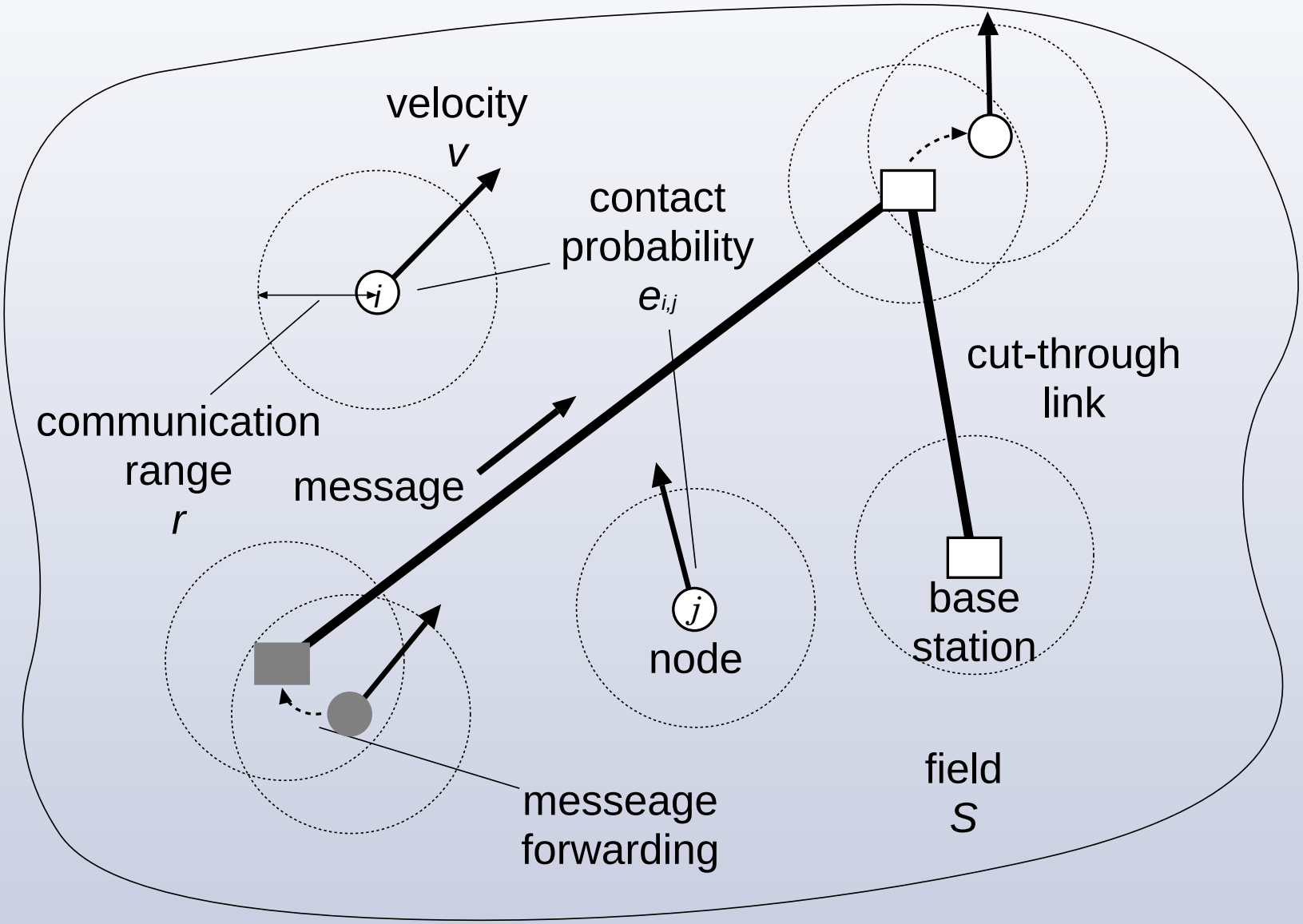
Existing works

- Simulation studies to investigate the effectiveness of cut-through links deployment for epidemic broadcasting

Our work

- Mathematically analyze the effect of cut-through links deployment for epidemic broadcasting

Analytic Model (1/2)



Analytic Model (2/2)

Message possession probability vector:

$$\pi(k)(= {}^t(\pi_1(k), \ldots, \pi_N(k))) \tag{1}$$

Contact probability matrix:

$$E = (e_{i,j}) \tag{2}$$

Message diffusion dynamics with P-BCAST can be approximated as

$$\pi(k+1) = (\mathbf{I} + \mathbf{E})\,\pi(k). \tag{3}$$

Assumptions

- The number w of cut-though links on the field
- $w + 1$ base stations are connected as a tree
- All cut-though links are sufficiently longer than the communication range r

Analysis (Case of Uniform Node Distribution) (1/2)

We assume that probability $p_i(x)$ that node i $(1 \leq i \leq N)$ exists at a point $\mathbf{x} \in S$ is uniform:

$$p_i(x) = p(x) = \frac{1}{|S|} \tag{4}$$

The expected duration τ of an encouter among nodes i and j is given by

$$\begin{aligned} \tau &= \frac{1}{2r} \left(2 \int_{-r}^{r} \sqrt{r^2 - x^2} dx \right) v^{-1} \\ &= \frac{\pi r}{2v}. \end{aligned} \tag{5}$$

Analysis (Case of Uniform Node Distribution) (2/2)

Contact probability $e_{i,j}$ among nodes i and j at a slot is given by

$$e_{i,j} = \begin{cases} \frac{\pi r^2}{|S|}\tau^{-1} = \frac{2rv}{|S|} & i \neq j \\ 0 & \text{otherwise} \end{cases}. \quad (6)$$

Virtual contact probability $e'_{i,j}$, which takes account of both direct and indirect encouters, is given by

$$e'_{i,j} = \begin{cases} e_{i,j} + (1 - e_{i,j})(\frac{\pi r^2}{|S|})^2 (w+1)\, w\, \tau^{-1} & i \neq j \\ 0 & \text{otherwise} \end{cases}. \quad (7)$$

Analysis (Case of Non-Uniform Node Distribution) (1/2)

We foucs on the case that the spatial distribution $p_i(\mathbf{x})$ of node i is given by an arbitrary function

Contact probability $e_{i,j}$ among nodes i and j at a slot is given by

$$e_{i,j} = \begin{cases} \tau^{-1} \int_S p_i(\mathbf{x}) \left(\int_{D(\mathbf{x},r)} p_j(\mathbf{y}) d\mathbf{y} \right) d\mathbf{x} & i \neq j \\ 0 & \text{otherwise} \end{cases} \tag{8}$$

where $D(x, r)$ is the disc centered at point x with radius r

Analysis (Case of Non-Uniform Node Distribution) (2/2)

Indirect contact probability of nodes i and j through base stations l and m ($\neq l$) is given by

$$\xi_{i,j}^{l,m} = \tau^{-1} \int_{D(\mathbf{z}_l,r)} p_i(\mathbf{x}) d\mathbf{x} \int_{D(\mathbf{z}_m,r)} p_j(\mathbf{x}) d\mathbf{x} \tag{9}$$

Thus, virtual contact probability $e'_{i,j}$ is given by

$$e'_{i,j} = \begin{cases} e_{i,j} + (1 - e_{i,j}) \sum_{1 \leq l,m \leq w+1,\ l \neq m} \xi_{i,j}^{l,m} & i \neq j \\ 0 & \text{otherwise} \end{cases} \tag{10}$$

Quantifying the Impact of Adding a Cut-Throuhg Link

- Introduction of an additional cut-through link (e.g., $w \rightarrow w+1$) reduces the message delivery delay
- Increasing the wireless communication range r also reduces the message delivery delay

Question

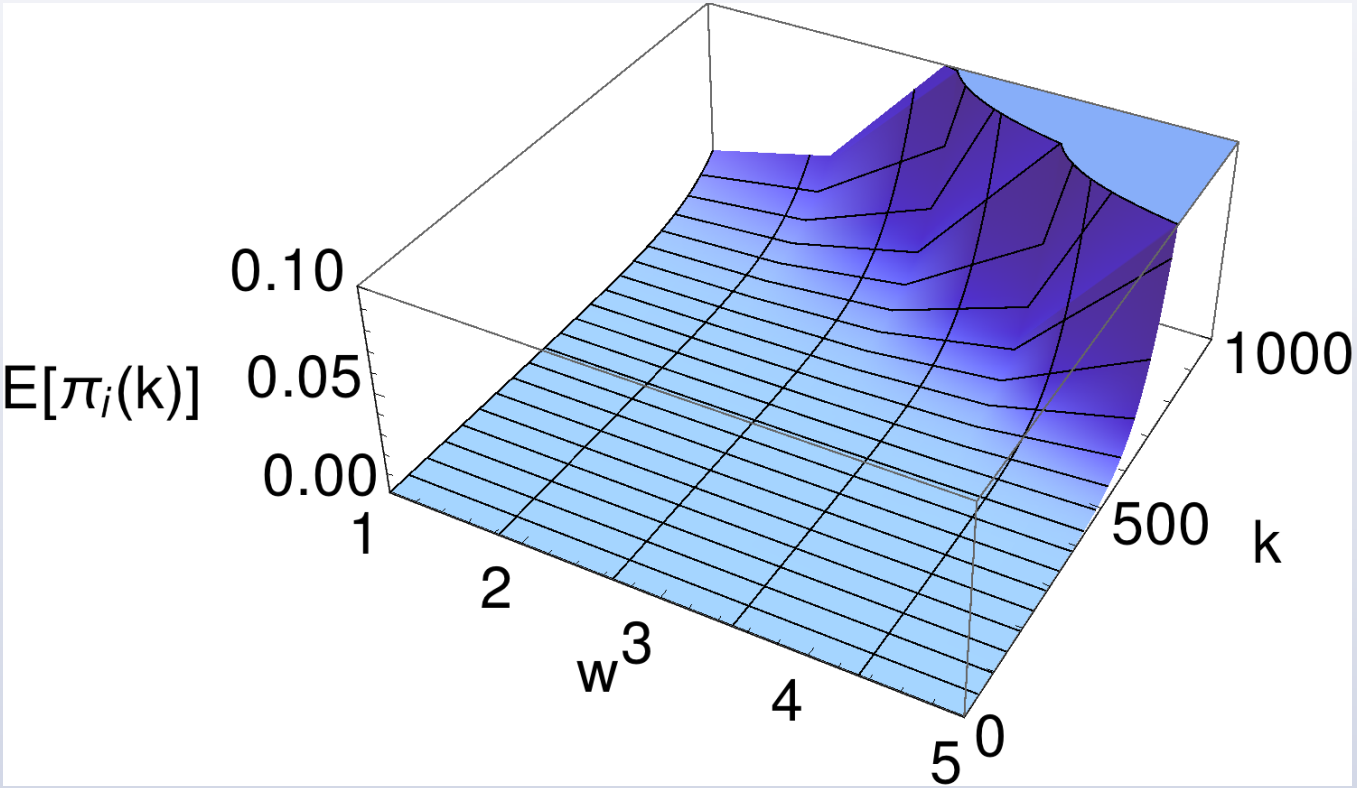
- How much increase in r is equivalent to an increment in w?

Solution

- Solve the following equation for Δr

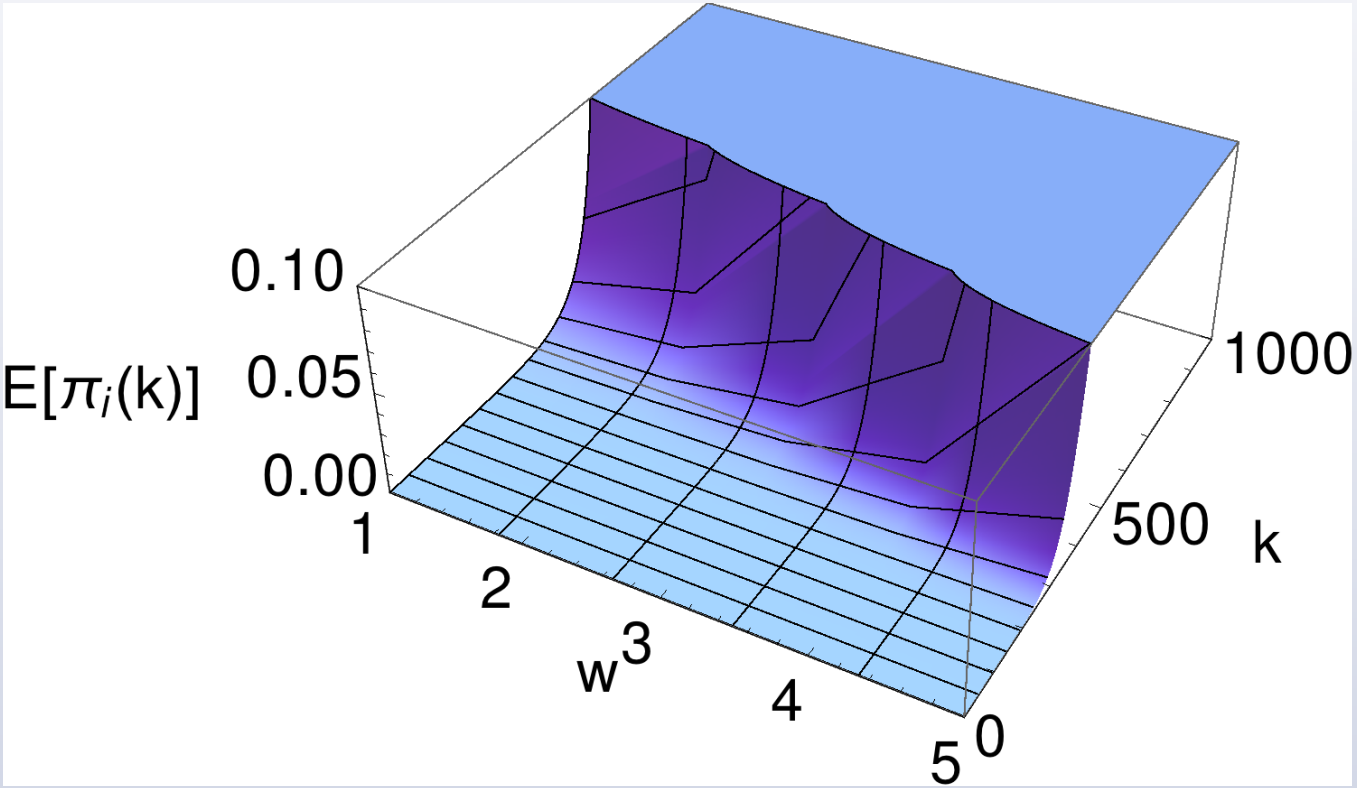
$$e'_{i,j}|_{w \rightarrow w+1} = e'_{i,j}|_{r \rightarrow r+\Delta r} \tag{11}$$

Numerical Example (Dynamics of Message Possession Probability) (1/3)



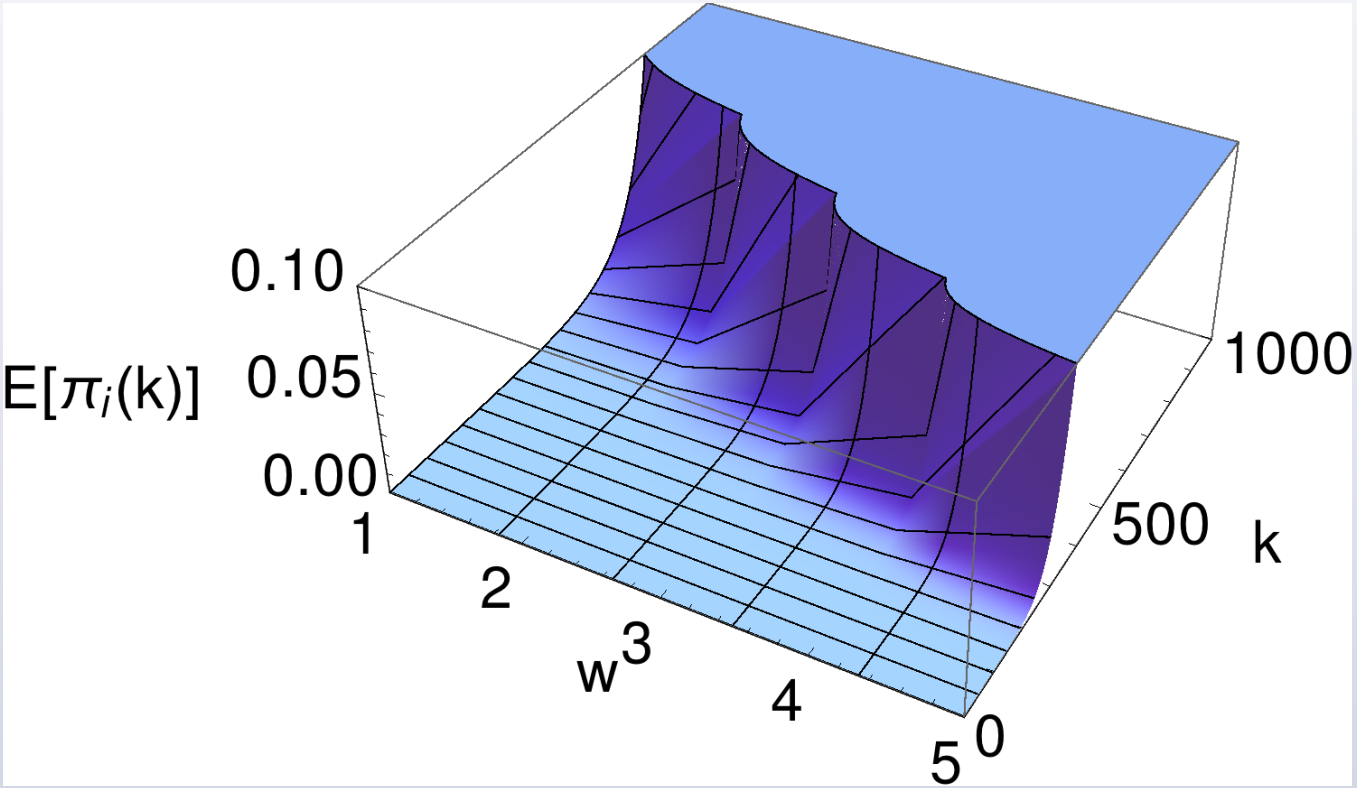
$N = 20$, $r = 50$ [m], $v = 4$ [km/h], $|S| = 250{,}000$ [m^2]

Numerical Example (Dynamics of Message Possession Probability) (2/3)



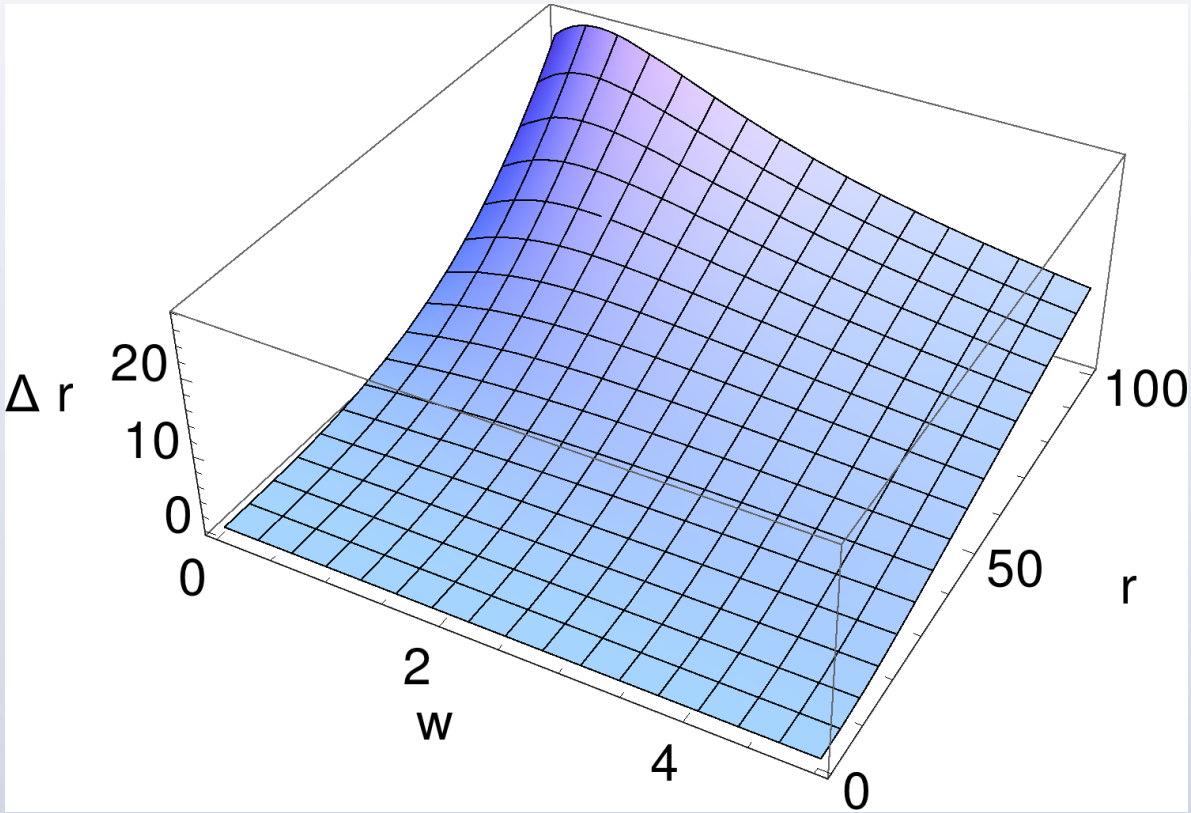
$N = 40$, $r = 50$ [m], $v = 4$ [km/h], $|S| = 250{,}000$ [m^2]

Numerical Example (Dynamics of Message Possession Probability) (3/3)



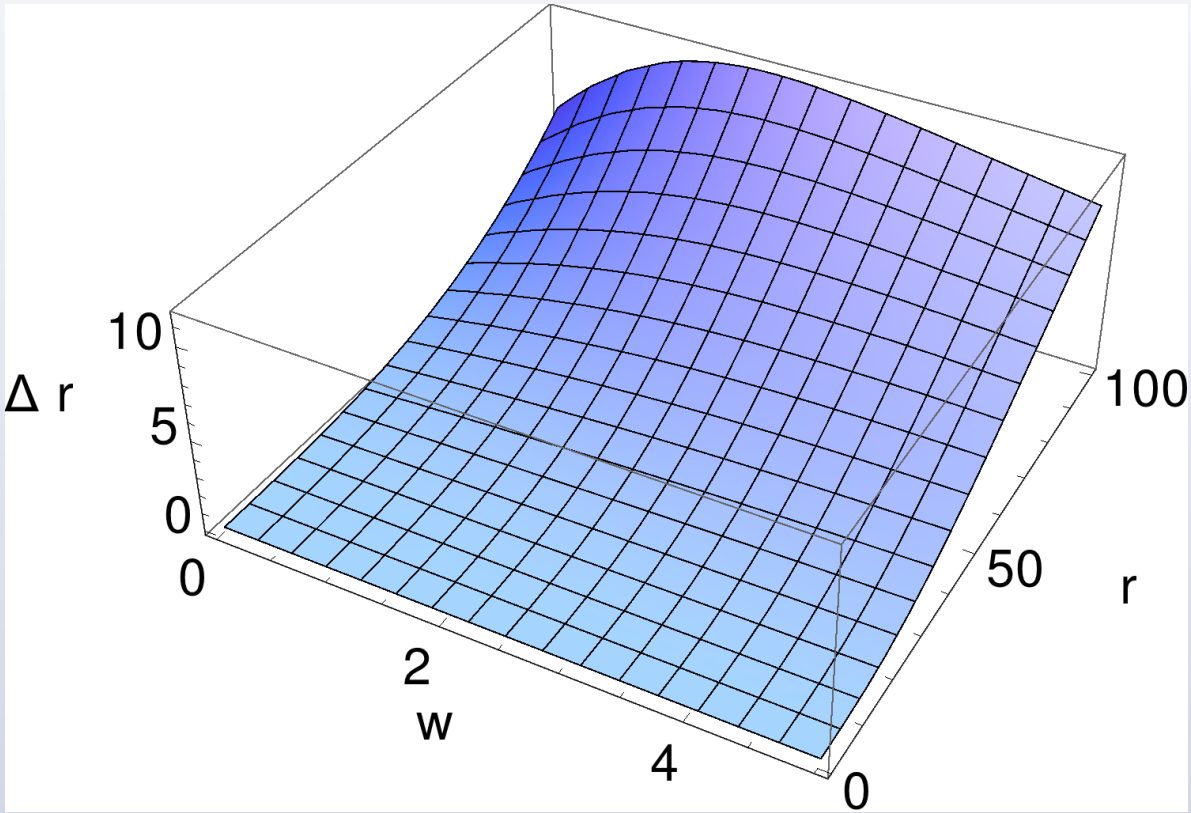
$N = 20$, $r = 75$ [m], $v = 4$ [km/h], $|S| = 250{,}000$ [m^2]

Numerical Example (Impact of Additional Cut-Through Link) (1/2)



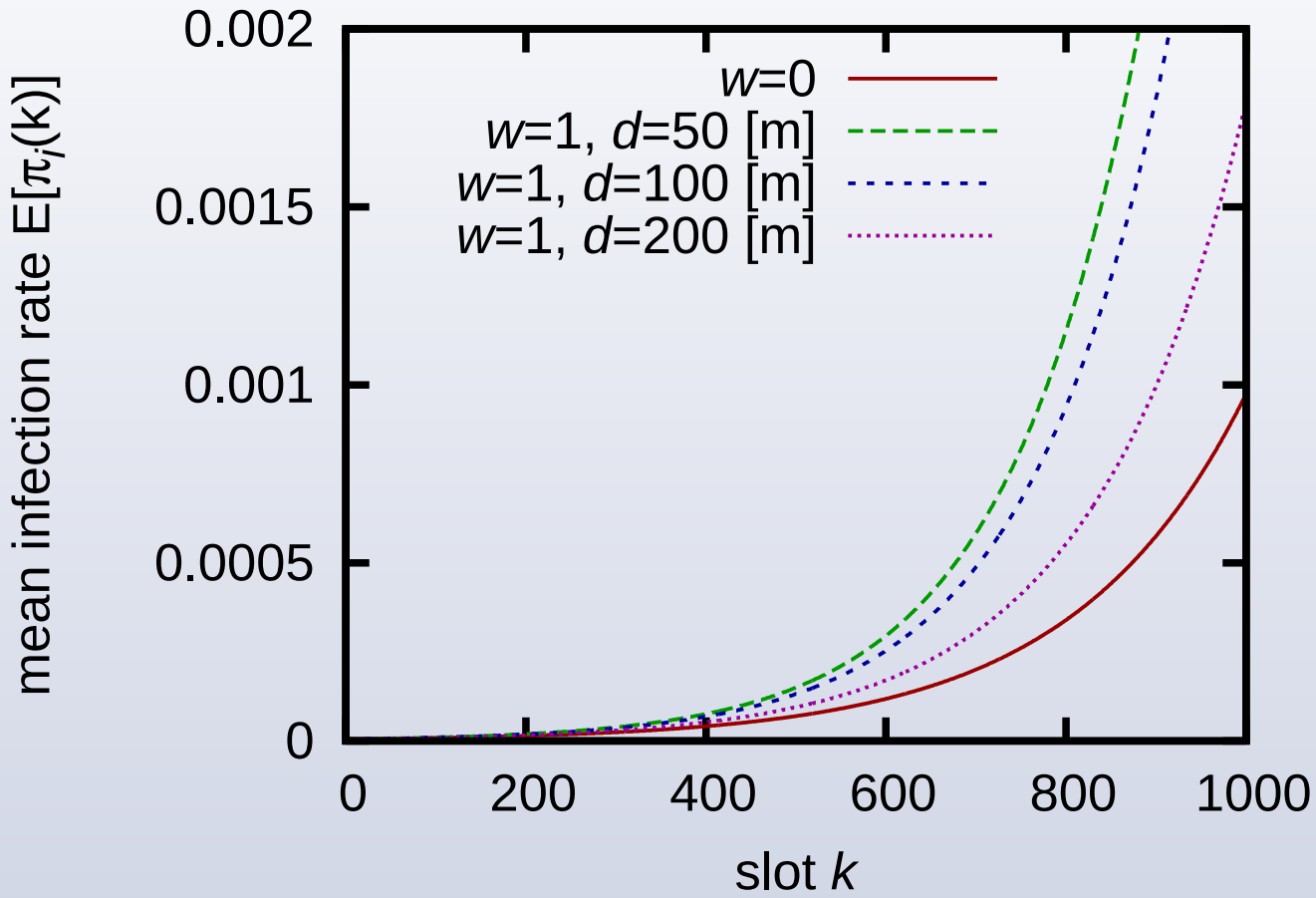
$N = 20$, $v = 4$ [km/h], $|S| = 250{,}000$ [m^2]

Numerical Example (Impact of Additional Cut-Through Link) (2/2)



$N = 20$, $v = 4$ [km/h], $|S| = 1{,}000{,}000$ [m^2]

Numerical Example (Case of Non-Uniform Node Distribution)



$N = 20$, $r = 50$ [m], $v = 4$ [km/h], $|S|$ = 250,000 [m^2], z_1 = (-d, 0), $z_2 = (d, 0)$

Conclusion

- Analyzed the message diffusion dynamics of epidemic broadcasting with cut-through links
- Quantitatively revealed the effect of deploying cut-through links on the performance (in particular, rapidity of message delivery)
  - Performance of epidemic broadcasting improves significantly…
    - by introducing a small number of cut-through links
    - by placing base stations appropriately according to the positional distribution of mobile nodes

Future Works

- Performance analysis of epidemic broadcasting algorithms other than P-BCAST
- Design a message routing mechanism utilzing cut-through links
- Design a buffer management mechanism of base stations